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Abstract

We suggest that Feature A, a ring of HI gas lying in the galactic plane, is part of a supershell which formed some 3×10^7 years ago. We examine the consequences of a closed magnetic supershell for cosmic ray propagation and conclude that there is no evidence which precludes the production and trapping of cosmic rays in such a region. A consequence of superbubble confinement is that the mean age of cosmic rays would be independent of energy (even though the grammage traversed is dependent on energy). This can be tested by high energy observations of the isotopic composition of Be.

1. Introduction

At Earth we observe cosmic rays which occupy an unknown volume of the galactic space around us. The conventional view is that cosmic rays pervade the whole galaxy, being trapped and held there by diffusive scattering from waves and inhomogeneities in the galactic magnetic fields (for a review of cosmic ray propagation, see Cesarsky, 1980).

Early on, however, Jokipii and Parker (1969) noted that the streaming velocity of cosmic rays associated with the observed anisotropy is so low that the distance travelled in a typical cosmic ray lifetime is only of the order of a few hundred parsecs. More recently, several analyses of other cosmic ray data have also led to the conclusion that the cosmic rays observed at Earth may be of relatively local origin. For example, from observations of the high energy electron spectrum up to 1 TeV, Nishimura et al. (1980) concluded that the average propagation distance is only around 300 pc. Ormes and Protheroe (1983) used HEAO-3 (Engelmann et al., 1981) composition data and measurements of the proton and helium spectra to 10^{14} eV (Gregory et al., 1981; Tasaka et al., 1982) to conclude that the cosmic ray storage region in a conventional leaky box model is less than 1 kpc in size. Stecker and Jones (1977) analyzing the gamma-ray intensity distribution from SAS-2 found that the results were in accord with galactic models having little or no halo.

Recent HI observations (Heiles, 1979; Hu, 1981) have revealed the existence of large expanding shell-like structures in the galaxy. Some of these shells range up to 1.2 kpc in radius, 2×10^{7} M_{0} in mass, and 10^{53} ergs in kinetic energy and have been called supershells.

Kafatos, Bruhweiler and Sofia (1981) have suggested that the low density region in which the solar system is located may be inside a supershell, i.e., the interior of a superbubble, and that the locally observed cosmic rays propagate primarily in this region. In this paper we present evidence indicating that the solar system may indeed be located inside a supershell and discuss possible consequences of this for the propagation of cosmic rays.

2. Superbubbles

In the model of the interstellar medium due to McKee and Ostriker (1977), a large fraction of interstellar space consists of hot interstellar tunnels due to supernova explosions in an inhomogeneous medium. The recent observation of a large number of supershells in our galaxy (Heiles, 1979; Hu, 1981) would suggest that when repeated supernova explosions occur at the same location, large almost spherical volumes may be occupied by low density hot interstellar gas, surrounded by a shell of cold HI gas. Superbubbles with dimensions up to about 1 kpc have also been seen in the Magellanic clouds (Meaburn, 1980).

Bruhweiler et al. (1980) have shown that such objects could be produced by the interaction of evolving OB associations with the interstellar medium. They considered the evolution of supershells parallel and perpendicular to the galactic plane taking into account the galactic gravitational field and the variation of interstellar density with distance above the plane. They concluded that at our location in the galaxy, gravitation will have little effect on the transverse dimension of a supershell for radii less than 500 pc, which would be attained after $\sim 3.7 \times 10^7$ years. Tomisaka, Habe and Ikeuchi (1981) have calculated the consequences of sequential supernova explosions in OB associations and shown that shell structures result with characteristics similar to the observed supershells. These "superbubbles" are predicted to expand with time, t, their radii being proportional to t^m with m in the range

0.25 to 0.5 depending upon ambient gas density and supernova rate. They are expected to break up at a characteristic age of several times 10^7 years.

2.1 Evidence for a Local Superbubble

Ultraviolet observations (Bohlin, Savage and Drake, 1978) as well as X-ray observations (see review by Tanaka and Bleeker, 1977) indicate that the solar system exists in a low density, high temperature region--quite different from the large scale average physical conditions of the interstellar medium. Studying the ultraviolet spectra of nearby white dwarfs, Bruhweiler and Kondo (1982) concluded that the solar system is located inside a region of very low density (10^{-2}--10^{-3} cm^{-3}) hot (10^5-10^6°K) interstellar medium.

Radio observations at 21 cm (Lindblad, 1967; Hughes and Routledge, 1972; Lindblad et al., 1973; Olano, 1982) of galactic plane velocity-longitude variations of neutral hydrogen provide evidence for a large expanding elliptical ring referred to in the literature as "Feature A". The location of Feature A with respect to the Sun and nearby stellar associations is shown in Figure 1. Feature A has semi-axes of ~ 210 pc and ~ 360 pc. A detailed calculation taking into account the effects of the braking force due to the interaction of the expanding gas and the ambient interstellar medium gives an age of 3.1×10^7 years as best fitting the observed 21 cm data (Olano, 1982). Hughes and Routledge (1972) noted that Feature A corresponds to the region occupied by Gould's Belt of stars, which has an estimated age of $3\text{-}9 \times 10^7$ years. Also, a density enhancement in the large scale distribution of dust (Lucke, 1978) within 50 pc of the galactic plane has recently been correlated with Feature A by Elmgreen (1982). He also suggests that the giant molecular clouds and OB associations in Orion, Perseus and Sco-Cen regions may have all been formed in response to expansion of the Lindblad ring (Feature A).

High latitude observations of HI gas (Mebold, 1972, Heiles and Jenkins, 1975) suggest that the systematic longitude-velocity variations associated with Feature A can be seen up to ~ 50° in galactic latitude. Takakubo (1974) has analyzed Gaussian components of low and intermediate velocity clouds of HI gas and his work shows that a local cavity referred to as "the low velocity hole" with a deficiency of clouds appears at 60°-90° latitudes. All of the observations above are consistent with the solar system being located inside a supershell associated with Feature A.

3. Cosmic Ray Propagation in a Superbubble

We examine here problems related to the production and propagation of cosmic rays in the interior of a supershell, i.e., in a superbubble. We assume:

a. A superbubble which expands such that its radius depends on the time since its formation, t_{SB}, as

$$r \propto t_{SB}^{0.5}. \tag{1}$$

b. All the interstellar matter which was initially within the superbubble has been swept out and resides in the shell.

c. Cosmic ray primary species are all produced with the same power-law momentum spectra at a constant rate throughout the age of the superbubble, i.e., the rate of production of species j is given by:

$$Q_j(p,t_{SB}) = q_j \; p^{-\gamma} \;\; \text{nuclei s}^{-1} \; (\text{GeV/c/nuc})^{-1}, \tag{2}$$

where p is the momentum per nucleon.

d. Cosmic ray nuclei travel freely throughout the interior of the superbubble and, on encountering the shell, diffuse into it and then back to the interior of the superbubble. The probability of escaping from the superbubble is assumed to be rigidity dependent but small at low energies.

e. Nuclear interactions occur with the swept-up matter in the shell. The average rate at which matter is traversed per unit time (irrespective of whether the cosmic ray is in the shell or its interior) is assumed to be independent of the age of the superbubble, depending only on a particle's rigidity.

3.1 Trapping and Acceleration of Cosmic Rays within a Superbubble

If there is confinement of cosmic rays in a superbubble, we would expect it to be due to the magnetic field configuration in the shell. Unfortunately, there is no existing theory for the field configuration in an expanding supershell (Vallee, 1982). One would expect, however, that superbubble expansion would result in a relatively low field region towards the interior of the shell surrounded by an increasingly high field region, the field lines being stretched tangentially along the shell. Although the material in the shell during its later stages of expansion may be mostly neutral hydrogen as implied by 21 cm observation, one would expect a sufficient fraction to be ionized by starlight UV to keep the fields frozen to the matter concentrations.

We have found that a field stretched tangentially in the shell of superbubble aligned with Feature A can explain some features in the local galactic magnetic field as observed using starlight polarization (Mathewson and Ford, 1970) and rotation measures of extragalactic radio sources (Simard-Normandin and Kronberg, 1980) as will be discussed elsewhere.

Using the Zeeman effect, Troland and Heiles (1982) have measured a line-of-sight field of 7 microgauss in the 300 pc diameter Eridanus shell. They infer a field of 15 microgauss in the shell and argue that this will lead to dynamic effects which limit the density enhancements in the shell to approximately three times the original ambient medium density. If density enhancements are so limited and Feature A were part of a local supershell, we would estimate a shell thickness for Feature A of 50 to 100 pc (see Figure 1). This is of the order of 10^6 Larmor radii of a 1 TeV proton in a 10 microgauss field, so the wall is "thick" and can support considerable scattering even though the large scale field is ordered.

The matter encountered by cosmic rays is primarily in the shell of the superbubble. We envisage cosmic rays diffusing throughout the interior volume in a relatively free manner (large diffusion coefficient), occasionally encountering the shell in which magnetic fields and matter density are relatively high, and the diffusion coefficient is low. The result of a typical shell encounter could be diffusion into and along or around the shell before diffusing back into the interior of the superbubble. The energy dependence of the grammage in the present model would then be ascribed to energy dependent behavior of cosmic rays traversing the shell. Specifically, higher energy cosmic rays are required to spend less time in the shell than lower energy cosmic rays. If the magnetic field in the shell has been stretched tangentially, propagation along field lines would be mainly around the circumference of the shell so that the time spent in the shell would be determined mainly by cross-field diffusion. It is then possible to invoke, at least in an ad hoc way, spectra of magnetic field inhomogeneities which vary with depth into the shell to produce the required energy dependence of residence time of cosmic rays in the shell. For example, one might envisage a situation where low energy cosmic rays diffuse far into the shell while a higher energy cosmic ray would be returned more readily to the interior on experiencing a field which appears regular on the scale of its Larmor radius.

We turn now to a brief discussion of the acceleration of cosmic rays in a superbubble environment. If, as is suggested by Tomisaka et al. (1981), a superbubble forms as a result of OB association stars exploding sequentially as supernovae, we might expect a uniform rate of production of cosmic rays throughout the history of the superbubble, at least on timescales greater than the average interval between supernovae in the OB association. Cosmic rays could then be accelerated when the expanding shell of a supernova occurring within the cavity collides with the supershell, first order Fermi acceleration occurring as the supernova shock compresses particles against the relatively static wall. If this were the mechanism, there would be relatively little reacceleration of cosmic rays, since acceleration would be restricted in time to episodic supernovae and in space to relatively small volumes in or near the shell. This is required since if cosmic rays are accelerated throughout their lifetime, the energy spectra of secondary nuclei would not be appreciably steeper than those of primary nuclei (Eichler, 1980; Fransson and Epstein, 1980; Cowsik, 1980) contrary to observation.

Cassé and Paul (1980) have suggested that the shocked region at the boundary between stellar winds from O stars, B supergiants, T Tauri stars or Herbig-Haro objects and the surrounding medium could accelerate cosmic rays. Such an acceleration mechanism is also possible.

4. Predictions and Comparison with Observations

4.1 Energy Spectra and Composition at Low Energies

An immediate consequence of the expansion (assumption a) together with the trapping at low rigidities (assumption d) is that cosmic rays will be decelerated adiabatically,

$$\frac{dp}{dt} = -\frac{1}{2}\frac{p}{t_{SB}}, \tag{3}$$

where p is the momentum per nucleon. Thus, a particle observed now with momentum per nucleon, p, would have had a higher momentum per nucleon, p' at an earlier time when the superbubble's age was t_{SB}',

$$p' = p\left(\frac{t_{SB}}{t_{SB'}}\right)^{0.5}. \tag{4}$$

The total number of nuclei of a primary cosmic ray species j in the superbubble with momentum per nucleon ranging from p to (p+dp) is then, neglecting losses due to nuclear interactions, given by

$$N_j(p,t_{SB})\,dp \simeq \int_0^{t_{SB}} Q_j(p')\,dp'\,dt_{SB'}. \tag{5}$$

For a power law source spectrum (eqn. 2) this reduces to,

$$N_j(p,t_{SB})\,dp \simeq \int_0^{t_{SB}} Q_j(p)\,dp\left(\frac{t_{SB'}}{t_{SB}}\right)^{\frac{\gamma-1}{2}} dt_{SB'}, \tag{6}$$

or in terms of cosmic ray age $t = (t_{SB}-t_{SB'})$,

$$N_j(p,t_{SB}) \simeq \int_0^{t_{SB}} Q_j(p)\left(1-\frac{t}{t_{SB}}\right)^{\frac{\gamma-1}{2}} dt. \tag{7}$$

Hence,

$$N_j(p,t_{SB}) = \frac{2\, t_{SB} Q_j(p)}{(\Gamma + \gamma)} . \tag{8}$$

For primary cosmic ray species then, the quantity, $(1 - \frac{t}{t_{SB}})^{\frac{\gamma-1}{2}}$, in equation (7) is analogous to the cosmic ray age distribution in equilibrium models.

The full equation describing the propagation of an arbitrary species (but neglecting ionization energy losses) is

$$\begin{aligned}\frac{\partial N_i(p,t_{SB'})}{\partial t_{SB'}} &= Q_i(p) + \sum_{j>i} \{N_j(p,t_{SB'}) \frac{X(R)}{t_{SB} x_{ji}}\} \\ &-N_i(p,t_{SB'}) \{\frac{X(R)}{t_{SB} x_i} + \frac{1}{t_i^D(p)}\} + \frac{\partial}{\partial p} \{\frac{1}{2} \frac{p}{t_{SB'}} N_i(p,t_{SB'})\},\end{aligned} \tag{9}$$

where, $X(R)/t_{SB}$ is average rate of traversal of interstellar matter (g cm^{-2} /unit time) by cosmic rays of rigidity, $R = pA/Ze$; x_i is the interaction length of species i (g cm^{-2}); x_{ji} is the transformation length (g cm^{-2}) for $j \rightarrow i$ (spallation or decay); $t_i^D(p)$ is the mean decay time of species i at momentum per nucleon, p.

We have found that data on secondary to primary ratios, including that from the HEAO-3 experiment (Engelmann et al., 1981) may be fit with

$$X(R) = 40\, [1 + (\frac{1.88\ \mathrm{GV/c}}{R})^2]^{-3/2}\, R^{-0.65}\ \mathrm{g\ cm^{-2}}. \tag{10}$$

This has a slightly less steep rigidity dependence than the mean escape length in the leaky box model derived recently from the same data (Ormes and Protheroe, 1983). In the important region from 1-10 GeV/nuc, X(R) has a dependence on rigidity close to $X(R) \propto R^{-\nu}$, with $\nu \approx 0.5$.

We can now determine the momentum spectrum and age distribution of secondaries. From equation (8), we obtain

$$N_j(p,t_{SB'}) \simeq N_j(p,t_{SB}) \left(\frac{t_{SB'}}{t_{SB}}\right) \qquad (11)$$

for a primary cosmic ray species j. The rate of production of a secondary species i is then,

$$P_i(p,t_{SB'}) \simeq N_j(p,t_{SB}) \frac{X(R)}{t_{SB} x_{ji}} \left(\frac{t_{SB'}}{t_{SB}}\right). \qquad (12)$$

The present momentum per nucleon spectrum of the secondary species is then approximately

$$N_i(p,t_{SB})dp \simeq \int_0^{t_{SB}} P_i(p',t_{SB'})dp' \, dt_{SB'}. \qquad (13)$$

Then,

$$N_i(p,t_{SB}) \simeq \int_0^{t_{SB}} P_i(p,t_{SB}) \left(1 - \frac{t}{t_{SB}}\right)^{\frac{\gamma+\nu+1}{2}} dt. \qquad (14)$$

The quantity $\left(1 - \frac{t}{t_{SB}}\right)^{\frac{\gamma+\nu+1}{2}}$ is thus analogous to the age distribution of secondaries in equilibrium models. This distribution is shown in Figure 2 for $\nu = 0.5$ where it is compared with an exponential age distribution as in the leaky box model. Note that for small cosmic ray ages, the age distribution derived here is similar to that for a leaky box model with a mean escape time from the leaky box of $\sim 0.4 \times t_{SB}$.

Cosmic ray ^{10}Be data analyzed in the context of the leaky-box model yield a mean escape time of $\sim 10^7$ years (Wiedenbeck and Greiner, 1980; Garcia-

Munoz et al., 1981). This would then imply a superbubble age of 2.5×10^7 years based on the qualitative arguments above. The observed quantity, however, is the ratio of ^{10}Be to ^{9}Be from which the fraction of ^{10}Be which survived radioactive decay can be derived. We have, however, solved the full equation using the observed surviving fraction of ^{10}Be and obtained $t_{SB} = (2.9^{+1.3}_{-0.7}) \times 10^7$ This age of a superbubble which we require to fit the ^{10}Be data is in agreement with the dynamical age of Feature A, 3.1×10^7 years, derived from radio observations.

Antiprotons ($\overline{p}$) have been observed at energies lower than expected for secondary production in conventional models (Buffington, Schindler and Pennypacker, 1981). Because of adiabatic energy losses, the present model can give a significant low energy $\overline{p}$ flux. The predicted $\overline{p}$ flux appears to be too low by a factor of about 50 at around 300 MeV. At higher energies, the prediction is a factor of approximately 8 below the observed flux (Golden et al., 1979; Bogomolov et al., 1979). It may be possible to reconcile these discrepancies with the present model by the addition of separate $\overline{p}$ sources (Cowsik and Gaisser, 1981; Cesarsky and Montmerle, 1981; Kiraly et al., 1981) within a superbubble.

4.2 Variation of Cosmic Ray Intensity over Historical and Geological Time Scales

Estimates of the average flux of low energy cosmic rays bombarding solar system material (e.g., from the abundance of cosmogenic nuclides in meterorites) over timescales of ~ 400, ~ 4×10^5 and ~ 10^9 years are available and have been reviewed by Schaeffer (1974) and more recently by Reedy, Arnold and Lal (1983). They indicate the galactic cosmic ray intensity has not changed by more than a factor of order two when averaged over these timescales.

From equation (11), the cosmic ray density in the present model, $n_{CR} = N_{CR}/(\frac{4}{3}\pi r^3)$, as a function of time before present, t, is given by

$$n_{CR}(t) = n_{CR}(0)\ (1 - \frac{t}{t_{SB}})^{-1/2}, \tag{15}$$

for $t < t_{SB}$. The cosmic ray density averaged from the present to time t before present is then,

$$\overline{n_{CR}}\ (<t) = \frac{1}{t} \int_0^t n_{CR}(t')dt'. \tag{16}$$

The average cosmic ray density estimated from the abundance of cosmic ray produced nuclides in meteorites is plotted against "averaging time" before present in Figure 3. The cosmic ray intensity appears to have been almost constant over the past 10^6 years but was somewhat lower during the past 10^9 years (Schaeffer et al., 1981). Predictions based on the superbubble assumptions with $t_{SB} = 3 \times 10^7$ years are shown normalized to the present cosmic ray density. For $t > t_{SB}$ the expected intensity would be the average ambient galactic intensity, presumably lower than that inside a superbubble "source". We show two possibilities based on a cosmic ray density outside the superbubble which is arbitrarily set equal to the present cosmic ray density inside or to 2/3 of the present density.

If Feature A is part of a closed superbubble, the solar system is presently situated just inside the superbubble and it is likely that the solar system was engulfed by the expanding supershell approximately 10^7 years ago. Solar system material would then have experienced a lower cosmic ray density than that given by equation (16) between 10^7 and 3×10^7 years before present. Predictions based on this assumption are shown as the dashed lines in Figure 3.

It is clear from the figure that the data on the time variation of cosmic ray density which are presently available do not rule out the present model. Indeed, a model that does not rule out an intensity variation of ~ 50 percent between ~ 10^6 and 10^9 years ago would appear to be required by the data.

4.3 Anisotropy

The observed anisotropy of cosmic rays is thought to arise from bulk flow of cosmic ray gas with respect to the Earth. In the present model, such a flow would arise from leakage of cosmic rays from the superbubble. At low energies where leakage is assumed to be negligible, any anisotropy would be due to expansion of the superbubble or motion of the Earth with respect to the cosmic ray gas. For a velocity of bulk flow of cosmic rays past the Earth of v_B, the magnitude of the anisotropy is given by

$$\delta \approx (2 + \gamma)\, v_B/c, \tag{17}$$

where γ is the index of the differential energy spectrum. This takes into account Doppler shifts in the particle spectrum (Compton-Getting effect). If Feature A is indeed part of a closed superbubble, then we are relatively near to the shell. The nearest part of Feature A is moving outward with a velocity of 6 km/s with respect to the Earth. We would thus expect an anisotropy of magnitude $\delta \approx 10^{-4}$ at low energies. This is consistent with that observed below 10^{15} eV (see e.g., the reviews by Linsley, 1981; Watson, 1982). The direction of the anisotropy at low energies is from 3^h right ascension, consistent with flow towards the nearest wall (see Figure 1). This may, however, be fortuitous since the direction of the observed anisotropy may be related more to the particles' Larmor radii and the local magnetic field structure than to the direction of bulk cosmic ray flow (Hillas, 1983).

If we attribute the high energy (> 10^{15} eV) anisotropy to leakage from the superbubble, we may estimate the escape probability as a function of energy. A finite escape probability per wall encounter, $P_{esc}(R)$, will give rise to bulk motion of cosmic rays with streaming velocity v_B near the shell given by

$$v_B \approx P_{esc}(R)\ c \tag{18}$$

This will give rise to an anisotropy,

$$\delta \approx (2 + \gamma)\ P_{esc}(R), \tag{19}$$

which is of the same order of magnitude as the escape probability per wall encounter.

At energies where leakage of cosmic rays becomes important, we would then expect a steepening in the energy spectrum. This will occur when the escape probability multiplied by the average number of wall encounters per mean cosmic ray age, $\langle t \rangle$, is of order unity. If ℓ is a characteristic dimension of the superbubble, we expect an anisotropy of $\delta \approx (2+\gamma)\ell/c\langle t \rangle$ at an energy where the cosmic ray spectrum steepens. Using values of ℓ in the range 200 pc to 400 pc appropriate to Feature A, and taking $\langle t \rangle \approx 10^7$ years, we would expect $\delta \approx 1.5 - 3\text{x}10^{-4}$ in the region of the "knee" in the cosmic ray spectrum ($\sim 10^{15}$ eV). Again, this is consistent with that observed.

The direction of the observed anisotropy above 10^{15} eV is from 12^h-18^h right ascension (see e.g., Linsley, 1981; Watson, 1982) and changes with energy. As noted earlier this may not indicate the true direction of bulk cosmic ray flow. If this were the case, however, it would indicate a net flow from the nearby wall of the supershell suggesting a net inflow of cosmic rays. It is unlikely that the cosmic ray density outside a superbubble would be higher than that inside at these energies because the mean leakage time at these energies would be expected to be less than the expansion timescale of the superbubble and a net inflow could not then be sustained. Other possibilities, although highly speculative in nature, include: 1) Cosmic rays from exterior sources in the Sco-Cen active region may be "seen" through the partly transparent superbubble wall; b) A mini-superbubble (Weaver, 1978; Davelaar, Bleeker, and Deerenberg, 1980) may surround the Sco-Cen active region (Loop I, the North Polar Spur, may be the intersection of the two superbubbles) and contain a higher cosmic ray density which is now leaking into our superbubble; c) We are just seeing an anisotropy from the nearest acceleration region (i.e., the wall).

Just above 10^{17} eV, the abrupt reversal in the observed anisotropy direction may indicate a return to net outward flow of cosmic rays towards the local wall. This persists until about 5×10^{18} eV, which may indicate that above this energy the superbubble is completely transparent to cosmic rays.

4.4 Energy spectra and composition at High Energies

At high energies, where nuclear interactions can be neglected, the number of cosmic ray nuclei of type i within the superbubble will be given by:

$$\frac{\partial N_i(E,t_{SB})}{\partial t_{SB}} = Q_i(E) + \frac{\partial}{\partial E}\left\{\frac{1}{2}\frac{E}{t_{SB}} N_i(E,t_{SB})\right\} + \{\rho_i(E)V(t_{SB}) - N_i(E,t_{SB})\}\, t_L^i(E,t_{SB}) \tag{20}$$

where E is the total energy per nucleus, V is the superbubble's volume, ρ_i is the density of species i outside the superbubble, and t_L^i is the mean leakage time (in or out) of species i. This leakage time is assumed to be rigidity dependent $t_L^i(E) = \langle t \rangle\ (E/zeR_0)^{-\mu}$ where $\langle t \rangle$ is the mean cosmic ray age ($\sim 0.4\ t_{SB}$) and R_0 is the rigidity at which the present leakage time is equal to $\langle t \rangle$. R_0 and μ are chosen to fit the amplitude of the observed anisotropy above 5×10^{14} eV.

We have solved equation (20) for a simple two component composition model in which the cosmic rays contain only protons and Fe nuclei. The exterior cosmic ray spectrum is assumed to be a power law at all energies. A proton to iron ratio of 3:1 (at the same energy per nucleus) is assumed at production and the spectra are normalized to the data at 100 GeV/nucleus and 3×10^{18} eV/nucleus. The resulting energy spectra and composition are shown in Fig. 4 for three combinations of interior and exterior spectral index and escape parameters. The parameters used are given in Table 1. The observed energy spectrum and estimates of the composition are also shown in the figure.

Case I involves the minimum assumptions, i.e. that cosmic rays are produced inside the superbubble with a power law spectral index of -2.7, based on low energy observations, and the energy spectrum of cosmic rays outside the superbubble has the same spectral index. The power law of the escape probability variation with energy is taken to be $\mu = 0.6$, based on the observed energy dependence of anisotropy above 5×10^{14} eV. Cases II and III are arbitrarily modified to give different composition changes and spectral features in the region of the knee. There is considerable uncertainty attached to the energy spectra and composition at these energies but the present model is able to reproduce at least qualitatively some apparently related changes in the observed energy spectrum, composition and anisotropy.

In particular, features such as a "pulsar bump" (Karakula et al., 1974; Clay et al., 1983) can be produced together with composition changes at $\sim 10^{15}$ - 10^{16} eV which seem to be required by air shower data (e.g. Thornton and Clay, 1979; Andam et al., 1982). Such changes are at present controversial and we should also point out that other models with rigidity dependent leakage would give similar composition changes (e.g. Yodh, 1981).

6. Discussion

We have examined the possibility that the solar system may be located within a supershell, and what consequences this might have for the cosmic rays we observe at the Earth. We note that an expanding elliptical ring of HI gas in the galactic plane known as Feature A appears to extend above the plane of the galaxy and may be part of a supershell. In the region contained by Feature A there appears to be a marked deficiency of HI clouds at high latitude which further supports this suggestion.

We have considered the propagation of cosmic rays trapped in an expanding superbubble. Such trapping produces adiabatic energy losses of cosmic rays and leads to a unique age distribution of cosmic ray nuclei. Applying these considerations to the elemental and isotopic composition of cosmic rays we obtain the age of a superbubble required to fit the Be isotopic composition data. This age is consistent with the age of Feature A based on dynamical arguments. The observed anisotropy is also consistent with the superbubble picture. The high energy spectra and composition of the interior and exterior components can be mixed in such a way as to be consistent with the indirectly measured composition and all-particle spectra as deduced from a variety of ground based observation of air shower particles. The observed energy dependence of the matter traversed as reflected in the energy dependence of the charge composition of cosmic rays (secondary to primary ratios) is not a priori predicted by a superbubble confinement as discussed here. A more detailed argument involving energy dependent propagation in the superbubble shell must be found to explain this observation. However, we are unable to rule out this energy dependence. The evolving picture that low charge cosmic ray nuclei (p and He) have traversed more matter than heavier cosmic rays ($6 \lesssim Z \lesssim 28$) is also not explained, and neither is it in "standard cosmic ray propagation models."

An important aspect of superbubble confinement is that the mean age of cosmic ray nucleons (as opposed to the grammage traversed) is independent of energy. This may be tested by new measurements of isotopic abundances of radioactive secondary nuclides at energies above 10 GeV/nuc.

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	Differential spectrum index				Escape parameters	
	Interior		Exterior			
	p	Fe	p	Fe	R_0 (GV)	μ
I	2.7	2.7	2.7	2.7	2×10^6	0.6
II	2.7	2.7	3.05	3.05	2×10^6	0.8
III	2.7	2.6	2.7	2.6	3×10^5	0.6

Table 1 Spectral indices of cosmic rays inside and outside a superbubble and parameters describing the rigidity dependent escape used to obtain spectra and composition shown in Fig. 4.

Figure Captions

Fig. 1 Following Olano (1982), the expanding ring of gas, Feature A (stipple), is shown in the plane of the galaxy. The elliptical shape is the result of differential galactic rotation. The ring thickness shown represents an estimate of the shell thickness presuming Feature A is part of a superbubble.

Fig. 2 Age distribution of secondary nuclei in the present model (solid line) and in the leaky box model with a mean escape time of 0.4 x t_{SB} (dashed line).

Fig. 3 Variation of cosmic ray density averaged over the past 400, 4×10^6 and 10^9 years (•) from the work of Schaeffer (1974). Solid curves show variation expected in the present model if the cosmic ray density outside a supershell was (a) equal to, or (b) two thirds, of that inside. Dashed lines show variation if solar system was engulfed by a supershell ~ 10^7 years ago.

Fig. 4 (a) Integral energy spectra predicted for the three sets of model parameters in table 1, compared with data surveyed by Hillas (1981). (b) Differential energy spectrum for case I decomposed into components from interior and exterior p and Fe spectra. (c) Fraction of Fe predicted : hatched area corresponds to data of Goodman et al. (1979); thin bands refer to composition based on measurements of air shower mean depth of maximum and fluctuations by Chantler et al. (1983).

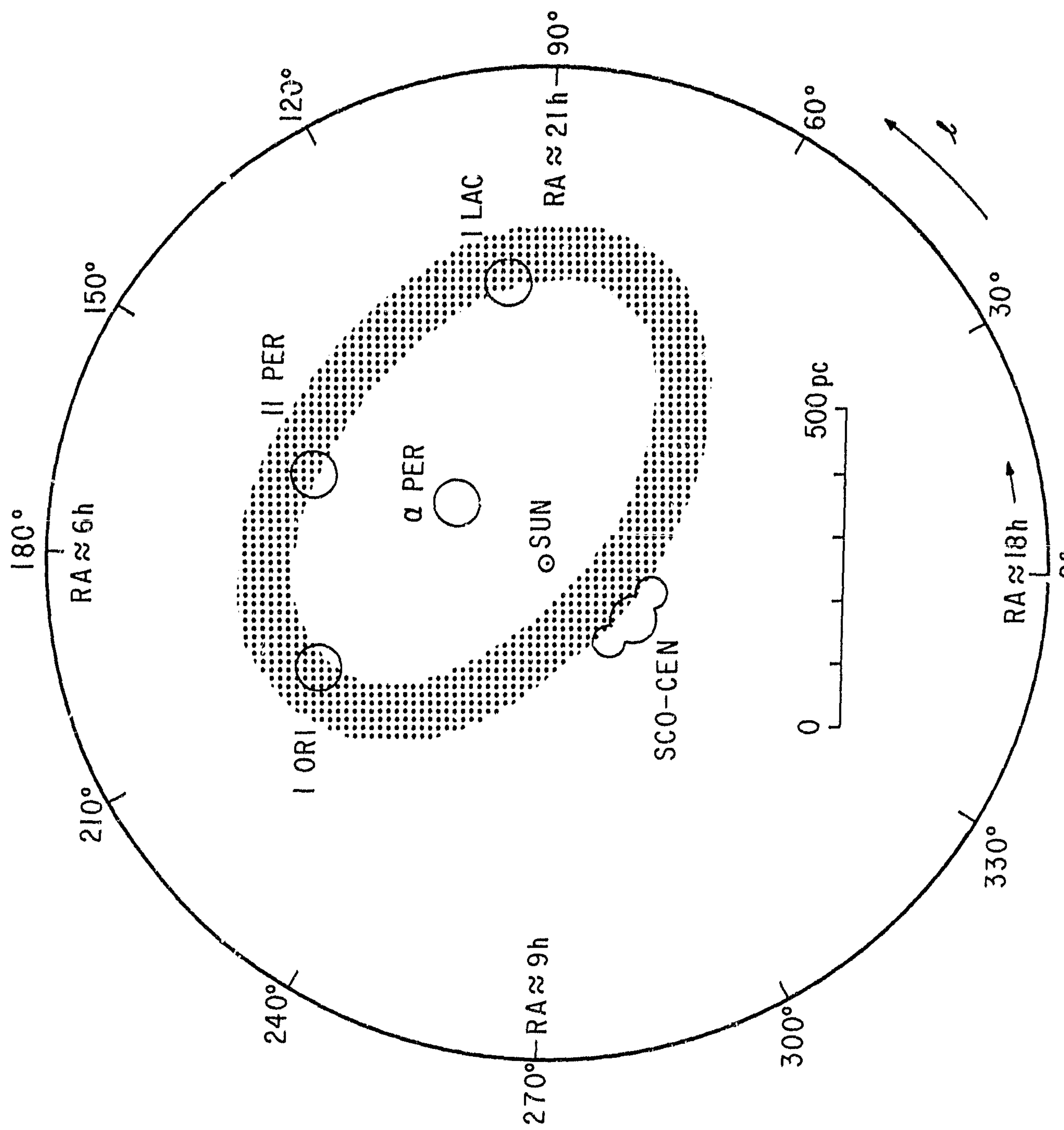

90°
120°
150°
180°
210°
240°
270°
300°
330°
0°
30°
60°
RA ≈ 21h
RA ≈ 6h
RA ≈ 9h
RA ≈ 18h
I LAC
II PER
α PER
SUN
I ORI
SCO-CEN
500 pc
0
ℓ

Figure 1

RELATIVE CONTRIBUTION OF SECONDARIES OF AGE t TO OBSERVED SPECTRUM

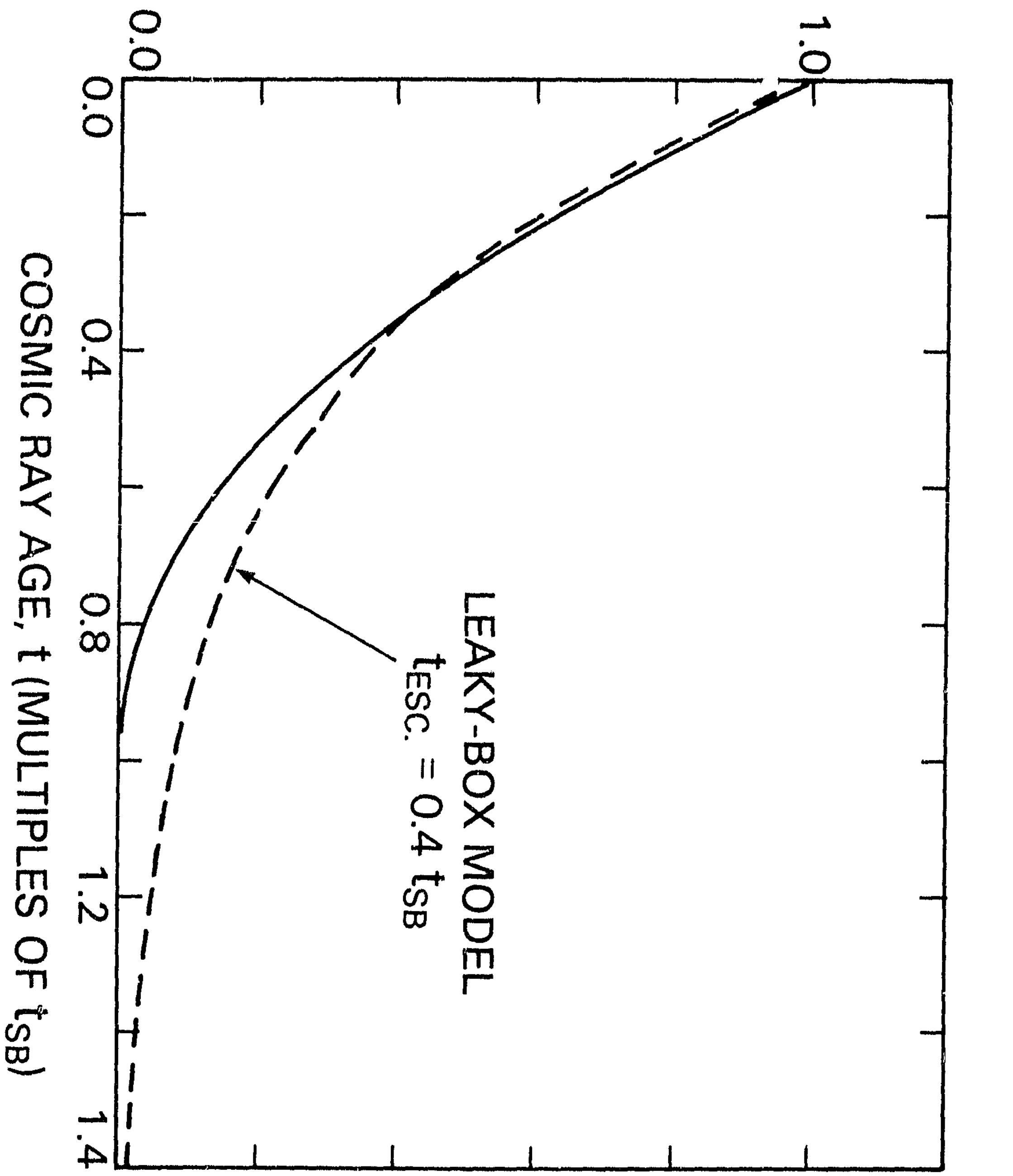
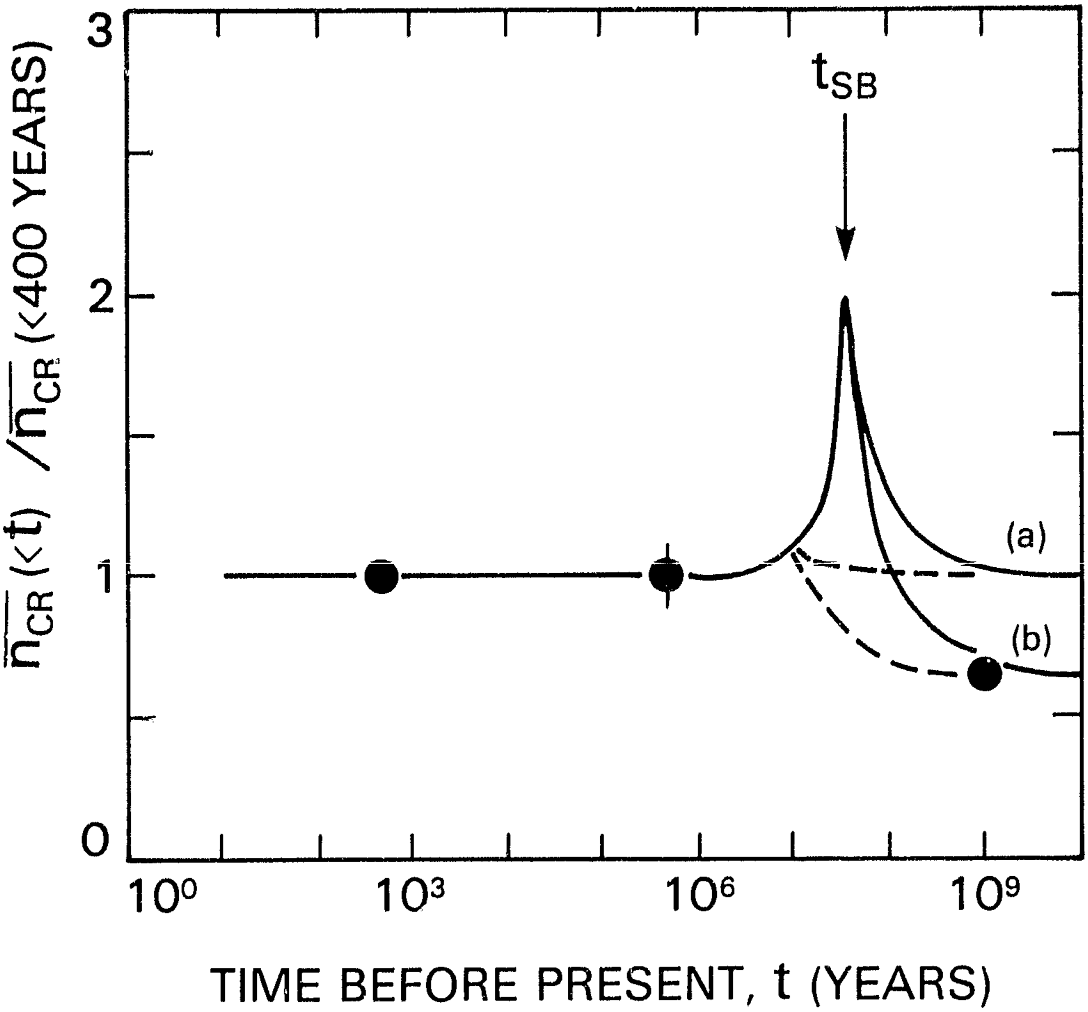
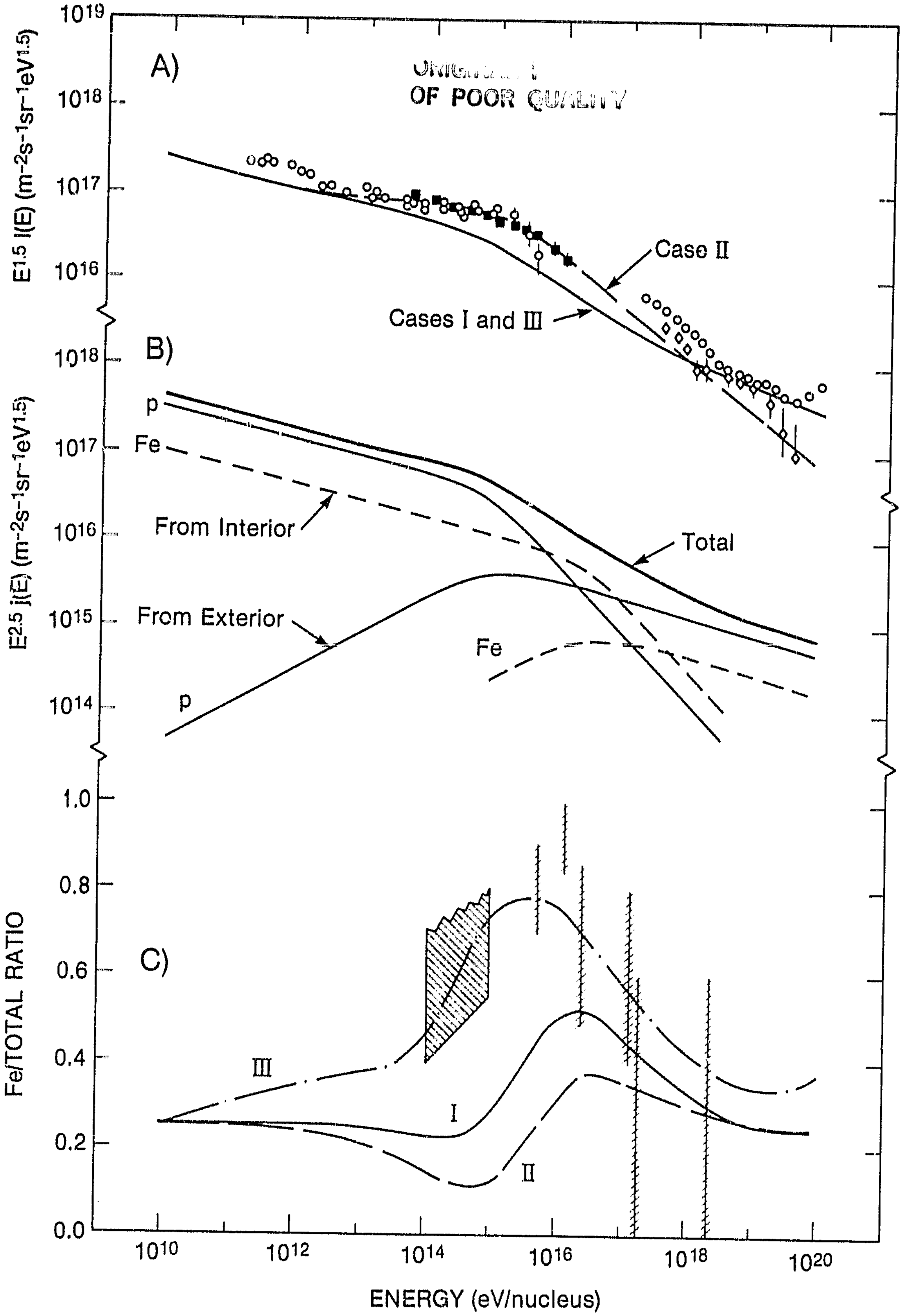


Figure 2



3
2
1
0
t_{SB}
(a)
(b)
10^0
10^3
10^6
10^9
TIME BEFORE PRESENT, t (YEARS)
$\overline{n_{CR}}(<t)\ /\overline{n_{CR}}\ (<400\ \text{YEARS})$

Figure 3



A)
ORIGINAL PAGE IS OF POOR QUALITY
Case II
Cases I and III
B)
p
Fe
From Interior
Total
From Exterior
Fe
p
C)
III
I
II
Fe/TOTAL RATIO
ENERGY (eV/nucleus)

Figure 4